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A TECHNIQUE FOR THE DIRECT FREQUENCY COMPARISON AND CONTINUOUS RECORDING OF FREQUENCY STANDARDS

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ABSTRACT

In the field of frequency and time determination it is often necessary to determine the frequency difference between two "standard" oscillators. This presents a difficult problem since the difference in frequency may be in the order of parts in 10^9. The technique herein described performs this task by comparing the frequency of a base standard with that of a similar standard and recording the difference directly in ± parts in 10^6, 10^7, 10^8 or 10^9 without necessitating the offsetting of either frequency.

PROBLEM STATUS

This report is an interim report on the problem. Work is continuing.

AUTHORIZATION

NRL Problem R10-26R

NR 510-260

A TECHNIQUE FOR THE DIRECT FREQUENCY COMPARISON AND CONTINUOUS RECORDING OF FREQUENCY STANDARDS

The accuracy required of controlling oscillators has increased, with the extended uses of electronic equipment, to such an extent that it has become increasingly difficult to make comparisons or to determine frequency characteristics to a sufficient degree of accuracy. In the case of crystal-controlled oscillators used as standards, the short time-frequency variation or the discrepancy between two such standards may consist of only a few parts at 10^9. Difficulty in performing this measurement arises from the fact that no reference standard is available which permits a greater precision in measurement than the frequency standard itself. Another frequency standard is therefore used as the reference.

Various methods have been devised to perform this measurement. The most used of these embodies the principle of counting cycles for a given length of time. The count can be made of the total number of cycles for each oscillator, in which case the count is made by an instrument and the difference calculated, or the two frequencies can be heterodyned and the difference-beat counted.

In the latter case the difference-beat can be recorded against time, thereby producing a continuous record. This method has been used at the Laboratory with quite satisfactory results. However, like most others, it is not a direct method in that some interval of time is always required to make the determination. For instance, the time required to complete one cycle of a difference-beat of 1 part in 10^9 at 5 Mc is 3 minutes 20 seconds. This difficulty may be overcome to some extent by multiplying the signals to higher frequencies before making the comparison. For instance, one part in 10^9 at 1000 megacycles creates a difference-beat of one cycle in one second.

Another solution is to offset one of the base frequencies by a definite amount such that the difference-beat is sufficiently large to be multiplied. Any discrepancy which appeared on the original frequencies is then multiplied by the same amount. The error can then be determined either by calculation or by a recording frequency meter. Such a method immediately indicates the value of frequency-difference at one predetermined power, such as parts in 10^8. However, the method is unusable in many applications because of two major disadvantages: namely, various powers of 10 cannot be selected easily and one frequency must always be offset. Another frequency standard may still be needed to determine the amount of offset or drift in the variable standard. Most frequency standards are held within narrow limits since they are usually maintained as frequency bases for other types of equipments.

It is evident that a need exists for a technique which permits the instantaneous determination of frequency-difference between two standards to a very high degree of accuracy without necessitating the offsetting of one of the oscillators. It is also advantageous to make a continuous recording of this difference against time. It is desirable to have the data obtained appear as percentage or as parts of the powers of 10, i.e., 10^8, 10^9, etc. since these are the most used and easily understood means of stating frequency difference or error. It is the purpose of this report to describe such a technique and an arrangement of circuitry which will realize it.

TECHNIQUE

When a frequency $(f + \Delta f)$ is added to or subtracted from a standard frequency f_s the magnitude of the error Δf is not altered,[1] i.e.

$$f_s + (f + \Delta f) = (f_s + f) + \Delta f \text{ and } f_s - (f + \Delta f) = (f_s - f) - \Delta f.$$

However, if the same frequency $(f + \Delta f)$ is multiplied or divided, the magnitude of the error Δf will vary directly with the factor of multiplication or division. An error Δf which exists at f will be $1/5\Delta f$ at $1/5f$, $2\Delta f$ at $2f$, etc. If a frequency $(f_1 + \Delta f_1)$ is multiplied in decade steps the outputs will be as follows: $(f_1 + \Delta f_1)$, $(10f_1 + 10\Delta f_1)$, $(100f_1 + 100\Delta f_1)$, etc. A series of frequencies can be derived from a standard reference source f_s such that any selected frequency of the series appears at a constant difference $-f_a$ from one of the decade multiples of f_1 as long as the accuracy of f_1 and of f_s remains equal. If the frequencies appearing at each decade step are combined in a mixer and the difference taken, the outputs will be as follows:

Unknown	Known	Output
$(f_1 + \Delta f_1)$	$- (f_1 - f_a)$	$= f_a + \Delta f_1$
$(10f_1 + 10\Delta f_1)$	$- (10f_1 - f_a)$	$= f_a + 10\Delta f_1$
$(100f_1 + 100\Delta f_1)$	$- (100f_1 - f_a)$	$f_a + 100\Delta f_1$
$(10^n f_1 + 10^n \Delta f_1)$	$- (10^n f_1 - f_a)$	$= fa + 10^n \Delta f_1$

[1] *If Δf is separated from f then f assumes the same accuracy as f_S.*

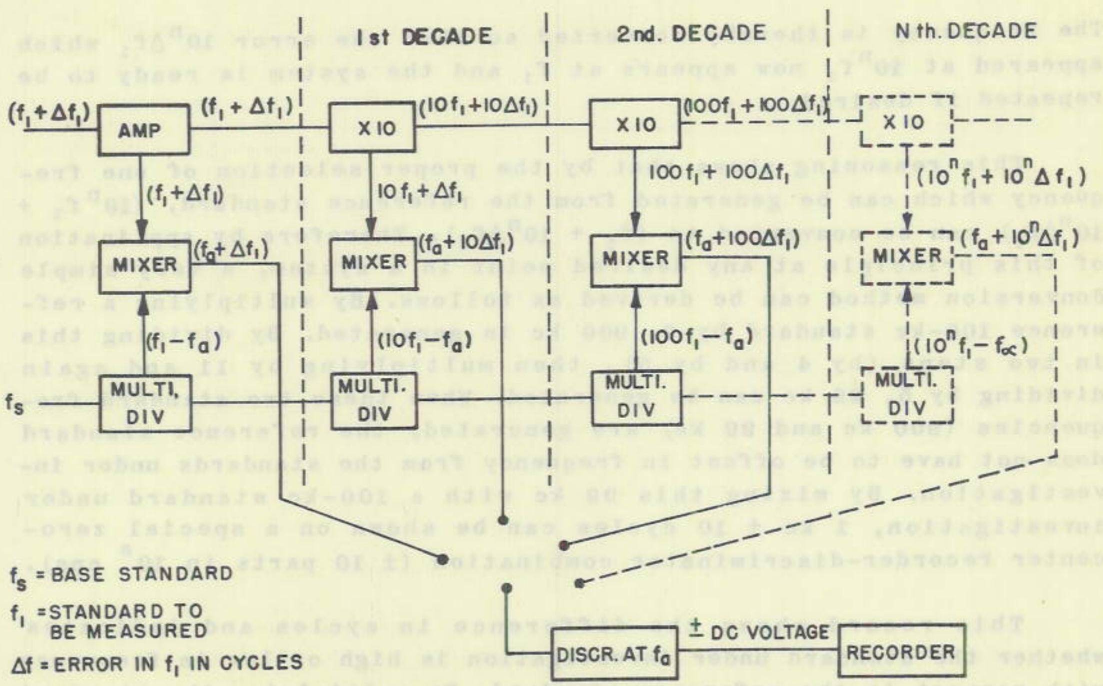

Figure 1 Diagram of technique

If the output from any one of the mixers at the decade steps shown in Figure 1 is fed into a frequency discriminator which produces zero output voltage at f_a, a d-c voltage will be produced which is proportional to the error frequency Δf at that particular decade step and which will indicate by its ± sign the direction in which the error lies. This voltage may then be recorded. If the decade multiples of f_1 in cycles are made to coincide with the powers of 10, the error frequency Δf_1 which exists at each decade step may be expressed as parts in the respective power of 10. I.e., an error of plus two cycles at 100 kc may be expressed as two parts in 10^5. Likewise the same error at 1 Mc would be 20 cycles or 20 parts in 10^6, etc.

Although this process theoretically may be continued indefinitely, a practical limit is quickly reached because of the fact that the frequencies involved increase with the decades. After several decades the multiplier circuits become extremely difficult to construct. If at the nth decade, where $(10^n f_1 + 10^n \Delta f_1) - (10^n f_1 - f_a) = (f_a + 10^n \Delta f_1)$, the value of the standard frequency is changed from $(10^n f_1 - f_a)$ to $(10^n f_1 - f_1)$, then the following is true:

$$(10^n f_1 + 10^n \Delta f_1) - (10^n f_1 - f_1) = (f_1 + 10^n \Delta f_1).$$

The frequency is thereby converted so that the error $10^n \Delta f_1$ which appeared at $10^n f_1$ now appears at f_1 and the system is ready to be repeated if desired.

This reasoning shows that by the proper selection of one frequency which can be generated from the reference standard, $(10^n f_1 + 10^n \Delta f_1)$ can be converted to $(f_1 + 10^n \Delta f_1)$. Therefore by application of this principle at any desired point in a system, a very simple conversion method can be derived as follows. By multiplying a reference 100-kc standard by 9, 900 kc is generated. By dividing this in two steps (by 4 and by 5), then multiplying by 11 and again dividing by 5, 99 kc can be generated. When these two standard frequencies (900 kc and 99 kc) are generated, the reference standard does not have to be offset in frequency from the standards under investigation. By mixing this 99 kc with a 100-kc standard under investigation, 1 kc ± 10 cycles can be shown on a special zero-center recorder-discriminator combination (± 10 parts in 10^5 cps).

This record shows the difference in cycles and indicates whether the standard under investigation is high or low in frequency with respect to the reference standard. By multiplying the standard under investigation by 10 (1000 kc) and mixing it with the 900 kc generated from the reference standard, a beat of 100 kc is obtained. When this is mixed with the 99 kc in the same mixer-discriminator-recorder combination, parts in 10^6 cps are indicated. By repeating this process over and over again and by proper switching means, parts in 10^7, 10^8, 10^9 up to 10^n are possible. Any frequency can be investigated by this system when properly converted to the input frequency.

EQUIPMENT

To confirm the theory of this technique an equipment, somewhat different from the example, was designed and constructed (diagram, Figure 2). This equipment employs 5 Mc as the input frequency for reasons stated later under "Frequency Deviation." It will be noted that f_1 is 1/5 the difference-beat between 5 Mc from the unknown and 4995 kc from the standard, f_s.

A standard base frequency of 100 kc (f_s), which for simplicity we shall consider as having no frequency error, is fed into a multiplier-divider system which produces upon separate jacks at its output 4995 kc, 999 kc, 99 kc and 9 kc. Since these frequencies are derived from f_s, all maintain the accuracy inherent in f_s. Another 100-kc signal, which for the present we shall also consider as having no error, is fed into a harmonic generator which multiplies it

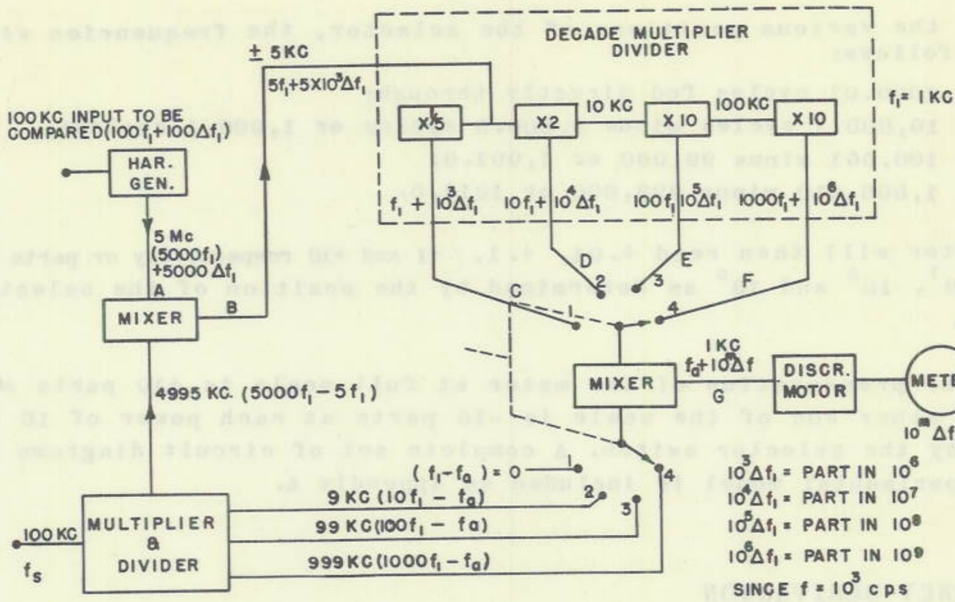

Figure 2 - Diagram of equipment

to 5 Mc. This 5-Mc signal is then beat in a mixer section with the 4995 kc obtained from f_s, thus producing a 5-kc ($5f_1$) output. This output drives a divider which produces 1-kc (f_1) and a decade multiplier which produces 10 kc, 100 kc and 1 Mc.

A switching system and mixer section follows. The switch is so arranged that the 999 kc, 99 kc and 9 kc derived from the standard can be mixed with 1 Mc, 100 kc and 10 kc respectively and separately thus producing an output in each case of 1 kc. (In the first position of the switch the 1 kc from a 5-1 divider is fed directly through the mixer.) The output of the mixer is then fed into a 1-kc discriminator which produces zero d-c voltage at 1 kc, a plus d-c voltage when the frequency is higher than 1 kc, and a minus d-c voltage when the frequency is lower than 1 kc. This voltage drives a one-milliampere zero-center d-c recording meter calibrated in conjunction with the discriminator so that a change of ± 10 cycles will cause the meter to read at the respective ends of the scale.

Suppose that the signal to be compared is 10 parts in 10^9 high in frequency with respect to the standard. The 5-Mc signal at point A (Figure 2) will be 5,000,000.05 cycles or +.05 cycle. At point B the signal is then 5,000,000.05 minus 4,995,000.00 or 5,000.05 cycles (.05 cycle high). Points C, D, E and F are then 1,000.01, 10,000.1, 100,001.0 and 1,000,010.0 cycles respectively. At point

G, for the various positions of the selector, the frequencies will be as follows:

(1) 1000.01 cycles fed directly through;

(2) 10,000.1 cycles minus 9,000.0 cycles or 1,000.1 cycles;

(3) 100,001 minus 99,000 or 1,001.0;

(4) 1,000,010 minus 999,000 or 1010.0.

The meter will then read +.01, +.1, +1 and +10 respectively or parts in 10^6, 10^7, 10^8 and 10^9 as determined by the position of the selector switch.

The presentation of the meter at full scale is +10 parts and at the other end of the scale is -10 parts at each power of 10 as shown by the selector switch. A complete set of circuit diagrams of the experimental model is included as Appendix A.

FREQUENCY DERIVATION

The choice of frequencies at which the system may be constructed to operate is governed by convenience and the desired sensitivity of measurement. The practical limit of sensitivity, at present, appears to be in the order of parts in 10^9. Most frequency standards, including those at the Laboratory, have a base frequency of 100 kc. Also, most locations have provisions for receiving the radiated signal from WWV at 5 Mc. The system was therefore designed from a base frequency of 100 kc with the first mixing taking place at 5 Mc. A difference-beat of 5 kc ($5f_1$) was chosen since a multiplication of 200 to 1 Mc will give a measurement sensitivity of parts in 10^9. It was also decided that parts in 10^6, 10^7, 10^8 and 10^9 would provide sufficient coverage for most applications. However, it is recognized that lower or higher orders of sensitivity may be similarly derived.

One kc was chosen as f_a, the operating frequency of the discriminator, because the 999 kc needed to produce f_a at 1 Mc is easily obtained by a direct division by 5 of 4995 kc which produces the original 5 kc. It will be noted that in the arrangement shown in Figure 2 the input frequency is not limited to 100 kc but may be 5 Mc or any division thereof. Also no 1 kc occurs in the arrangement except as derived for the discriminator, thereby preventing errors which would occur in the discriminator due to the presence of extraneous 1-kc signals.

Given several frequencies which must be derived from one source, a simple method which will provide the necessary information as to the minimum number of multiplications and divisions necessary to perform the operation, is as follows:

Since frequencies can only be multiplied or divided by whole numbers, the number of prime factors into which the frequency can be separated is its greatest number of divisions. If given two frequencies f_{source} and $f_{derived}$, one of which must be derived from the other, the following relation is true:

$$f_s \cdot \frac{f_d}{f_s} = f_d .$$

If the numerator and denominator be broken into their prime factors and the common factors canceled, the remaining fraction will indicate the operations necessary on f_s to produce f_d. This relation, though simple, is extremely useful when more than one frequency must be derived from the source.

For example: In the application at hand, frequencies of 4995 kc, 999 kc, 99 kc and 9 kc must all be derived from the 100-kc standard source. If these frequencies are broken down as shown above, the following equations result which immediately show the various orders of operations possible.

$$100 \cdot \frac{5\cdot3\cdot3\cdot3\cdot37}{5\cdot5\cdot2\cdot2} = 4995 \qquad 100 \cdot \frac{3\cdot3\cdot3\cdot37}{5\cdot5\cdot2\cdot2} = 999$$

$$100 \cdot \frac{3\cdot3\cdot11}{5\cdot5\cdot2\cdot2} = 99 \qquad 100 \cdot \frac{3\cdot3}{5\cdot5\cdot2\cdot2} = 9$$

By examination of the above equations it will be seen that the factor $3\cdot3/5\cdot2\cdot2$ is common to all equations. The first step, therefore, should satisfy this operation. It will also be noted that 999 is $1/5 \cdot 4995$, that 99 is $11\cdot9$ and that 9 is 1/5 the common factor $3\cdot3/5\cdot2\cdot2$ times 100 or 45. The simplest arrangement is therefore:

$$100 \cdot \frac{3\cdot3}{5\cdot2\cdot2} = 45 \longrightarrow \cdot 3\cdot37 = 4995$$

$$4995 \downarrow \cdot 1/5 = 999$$

$$45 \downarrow \cdot 1/5 = 9 \longrightarrow \cdot 11 = 99$$

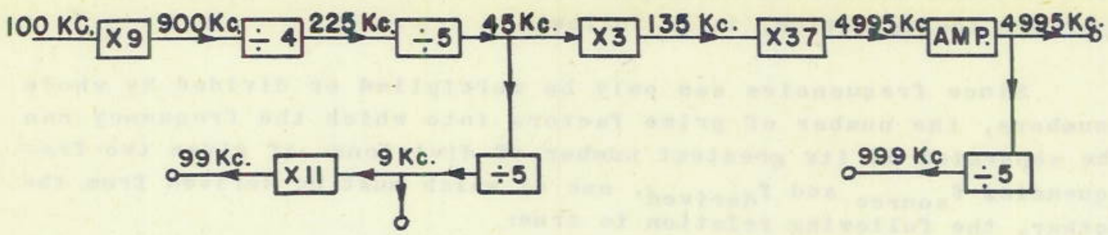

Figure 3 - Indicated circuit arrangement

In practice it is relatively simple to make stable circuits which multiply by 10 or more, or circuits which divide by 5 in one stage. The circuit arrangement in Figure 3 is therefore indicated.

For purposes of purity of the output signal, it is a good policy to keep the lowest frequency, in such a chain, as high as possible, since it may appear as a modulation component in the final output. Also it is desirable to follow each multiplier by a divider since the sidebands generated in the multiplication are greatly reduced by the division. For example in the first multiplier (Figure 3) 100 kc is raised to 900 kc and the first sidebands appear at 800 and 1000 kc. When the 4-1 division takes place in the second stage, the output is 225 kc making it much simpler for the tuned circuit to discriminate against the sidebands, the first of which is 450 kc, or the second harmonic of 225 kc.

A more desirable arrangement to produce 4995 kc would be obtained by rearranging the ÷ 5 and x3 stages of Figure 3, making the lowest frequency in the 4995 chain 135 kc instead of 45 kc. However this procedure necessitates the addition of one more stage in the 9-kc chain. In view of the filtering advantage gained (and borne out by experimentation) the final system was decided upon and constructed as shown in Figure 4. The prime factor (x37) prohibits any further change of the lowest frequency (135 kc) without undue complication of the system.

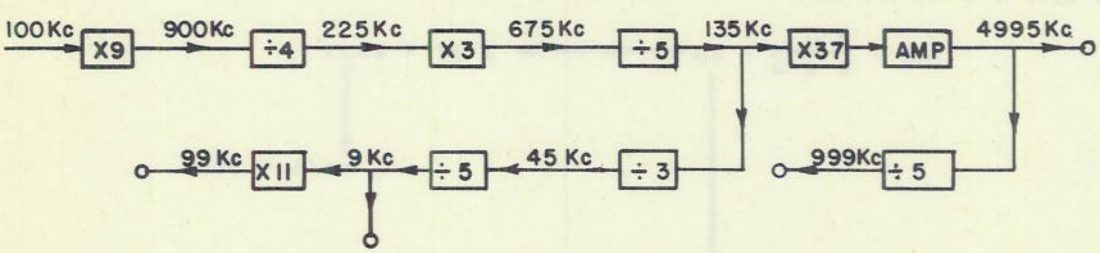

Figure 4 - Final circuit arrangement

The harmonic generators and mixers shown in the block diagram of Figure 2 (entire system) require special consideration only in that it is necessary to keep unwanted sidebands and modulations at a minimum. For further circuit details see Appendix A, Figures 7, 8, and 9.

DISCRIMINATOR-RECORDER

The only inherent errors in the entire system consist of those introduced by the discriminator or the discriminator-recorded combination.[2] Since the recorder is a simple ammeter, its reading is dependent upon the current fed through it from the discriminator. In the model constructed, a 1-ma, Esterline-Angus recording ammeter was used.

The selection of a suitable type of discriminator system presents a difficult problem in that the errors introduced must be negligible over long periods of time and recalibration must be quick and simple. No attempt is made in this report to discuss the relative merits of various discriminators. However, several types of discriminators were investigated. Tests were conducted on experimental models to determine possible sources of errors such as changes in circuit Q, plate potential, tuning capacities or inductances, filament variations, and other usual aging effects. The system developed may be described as follows.

Two parallel tuned circuits, one resonating on the high side and the other on the low side of a loosely coupled common sine-wave driving voltage, can be adjusted with respect to their Q's and resonant frequencies to produce equal voltages across each (Figure 5). In the model constructed the Q's were about 25 and the frequency separation about 4%. If the frequency of the driving voltage is lowered, the voltage across the circuit which is tuned low will increase and the voltage across the circuit which is tuned high will decrease. Likewise if the frequency of the driving voltage is increased the reverse will occur. When the voltages across the tuned circuits are rectified and applied to opposite sides of a differential voltmeter, the resultant reading of the meter gives an indication of the magnitude and direction of frequency changes made in the driving voltage. A calibration can then be made which will remain

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[2] *These errors constitute a constant-reading error, on the meter, which is independent of the preceding circuitry or input frequency.*

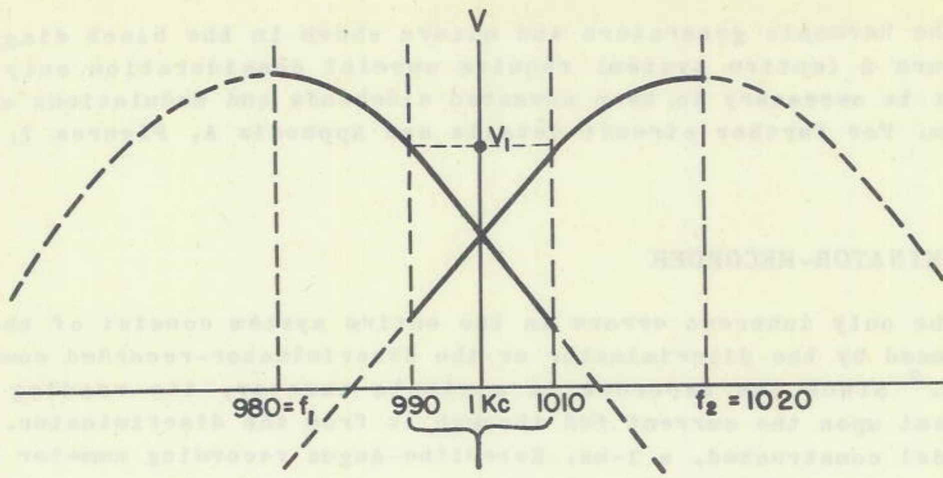

Figure 5 - Discriminator operation

correct so long as the driving voltage is constant and the frequency remains on the linear portion of the resonant curves (Figure 5).

In its actual usage in an equipment, this type of circuit must be preceded by some means of automatic voltage control. Two limiter stages and a double-tuned circuit were used in the model constructed. The outputs of the rectifiers are used to control the bias of a balanced d-c amplifier which in turn furnishes drive for the recorder (Figure 6).

It can be seen, by examination of the circuit, that the arrangement offers a great deal of flexibility since it allows a form of

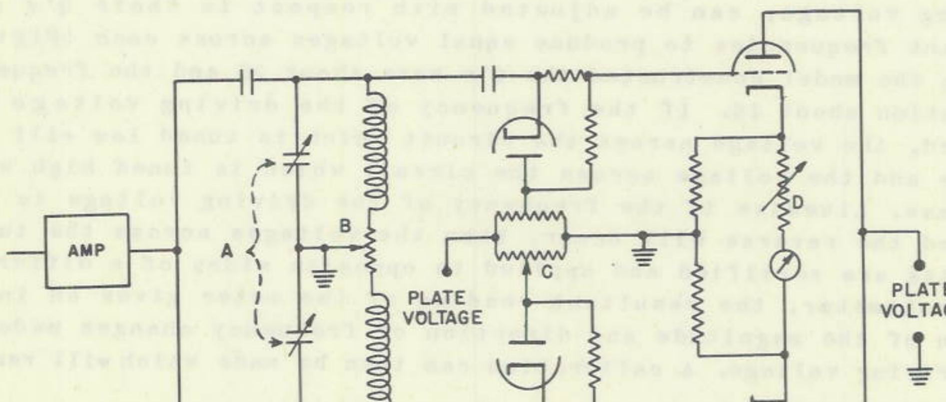

Figure 6 - Discriminator

compensation for each of the variables:

A. Output voltage and linearity

B. Relative Q of the tuned circuits

C. Inconsistancies between sections of the rectifiers or d-c amplifiers

D. Meter scale.[3]

A complete circuit diagram of the discriminator system is contained in Appendix A, Figure 10.

DISCUSSION OF ERRORS

As mentioned before, the only inherent errors in the entire system are those introduced by the discriminator. Since the discriminator operation takes place at low frequencies, it is relatively simple to keep circuit parameter variations negligible. Since the tuned circuits of the discriminator are of identical construction, their errors due to aging are likely to be similar. An error will appear, then, as a shift in the zero setting of the discriminator and therefore will be constant over the entire meter scale.

If the 100 kc to be compared is replaced by the reference standard 100 kc, the 1 kc which drives the discriminator will be correct to the same accuracy as the standard since all frequencies involved are derived from the same source. In this condition any deviation of the meter reading from zero will be an error. The discriminator system in the model constructed (which is in a temperature-controlled room) has shown a negligible drift in calibration during the several months it has been in operation. Any nonlinearity of the d-c meter movement will also present a constant error. The errors discussed above are all additive. Therefore their effect upon the final measurement is diminished as the order of sensitivity is increased. For example, the error at 10^9 is 1/10 of what it is at 10^8, etc.

It can be seen that sidebands which occur on the 1-kc output voltage and lie within the range of the discriminator will produce

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[3] *The external meter resistance in D of Figure 6 is large enough to permit a multiplication of the meter sensitivity by a factor of 10, thereby providing an extra multiple to record parts at 10^{10} when over-all stability of the oscillators permits.*

unwanted voltages which will affect the meter reading. If these sidebands are of unequal amplitude or if they lie off the linear portion of the discriminator curves, the meter will read in error. Special precaution must be taken to reduce these sidebands to a minimum. By experimentation most of this difficulty was found to be created by 60-cycle modulation from the filament circuits in the multiplication and mixer sections and 100-kc sources. The grounding of one side of the filament circuit was found to be necessary if ac was used. Also it was found beneficial to keep the cathode-to-ground impedance of all tubes as low as possible. D-c operation of all filaments is more desirable.

It must be recognized in the use of a system, as herein described, that the reference standard oscillator is considered as having no frequency error. The output data is all relative to the standard frequency, not to absolute frequency. Although the oscillators used in this method can be checked against one another to parts in 10^9, their errors relative to absolute frequency, based upon time, cannot be determined at the present time better than a few parts in 10^8.

CONCLUSIONS

A technique has been developed which may be employed to indicate, by direct reading or recording, the immediate or long-time frequency variation as related to a standard oscillator to a few parts in 10^9. Although its original purpose was to satisfy this need as applied to primary and secondary standards, the system has been found to be of great value in facilitating investigations in crystal and circuit studies where changes in parameters result in small frequency changes (Appendix B).

This technique can be applied to record any variable which can be converted to frequency change. For example, it could be adapted to measure extremely small temperature variation simply by including a temperature-sensitive element in the frequency-determining circuit such as the crystal in the oscillator producing f_1.

* * *

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APPENDI

CIRCUIT DI

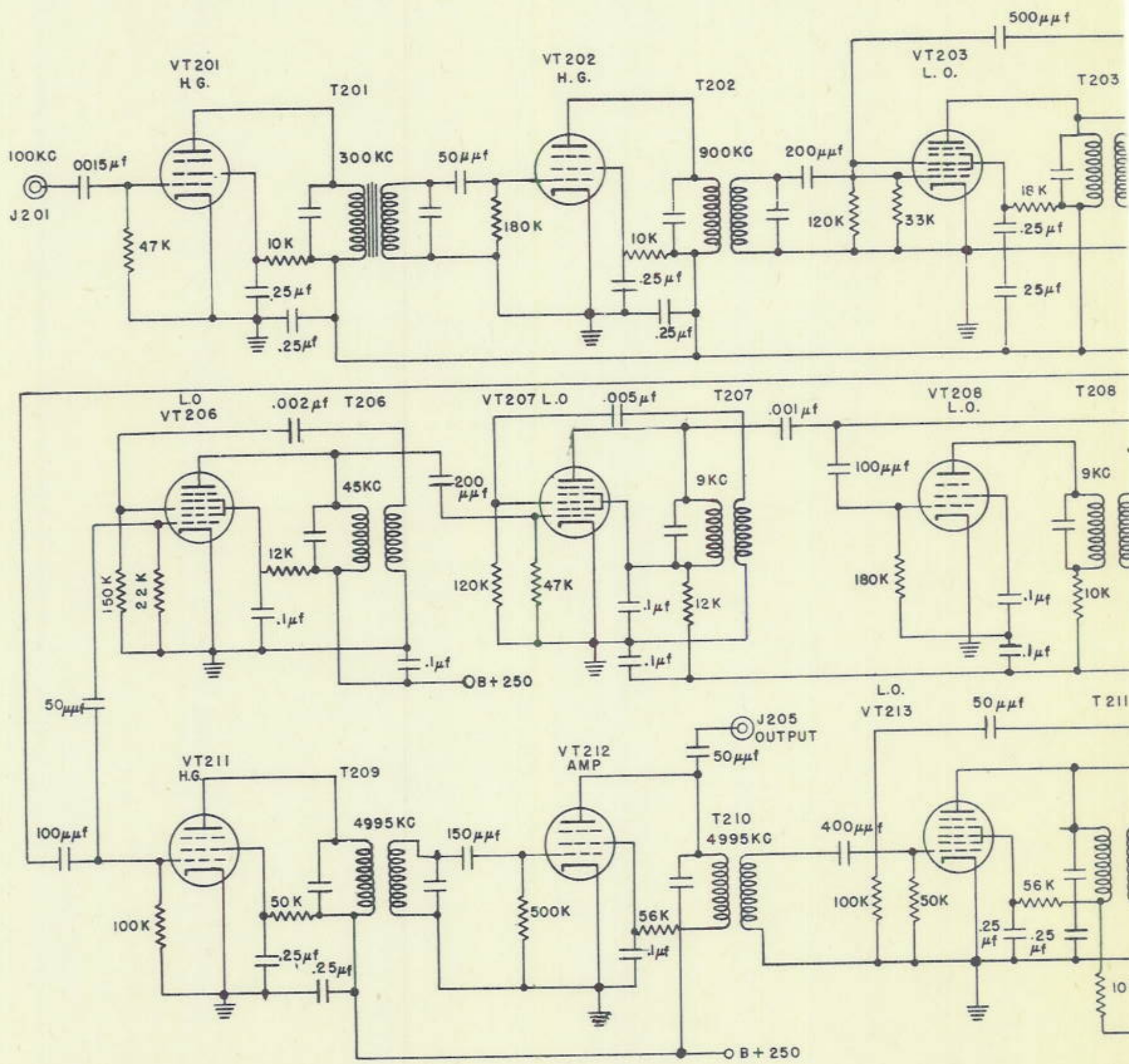
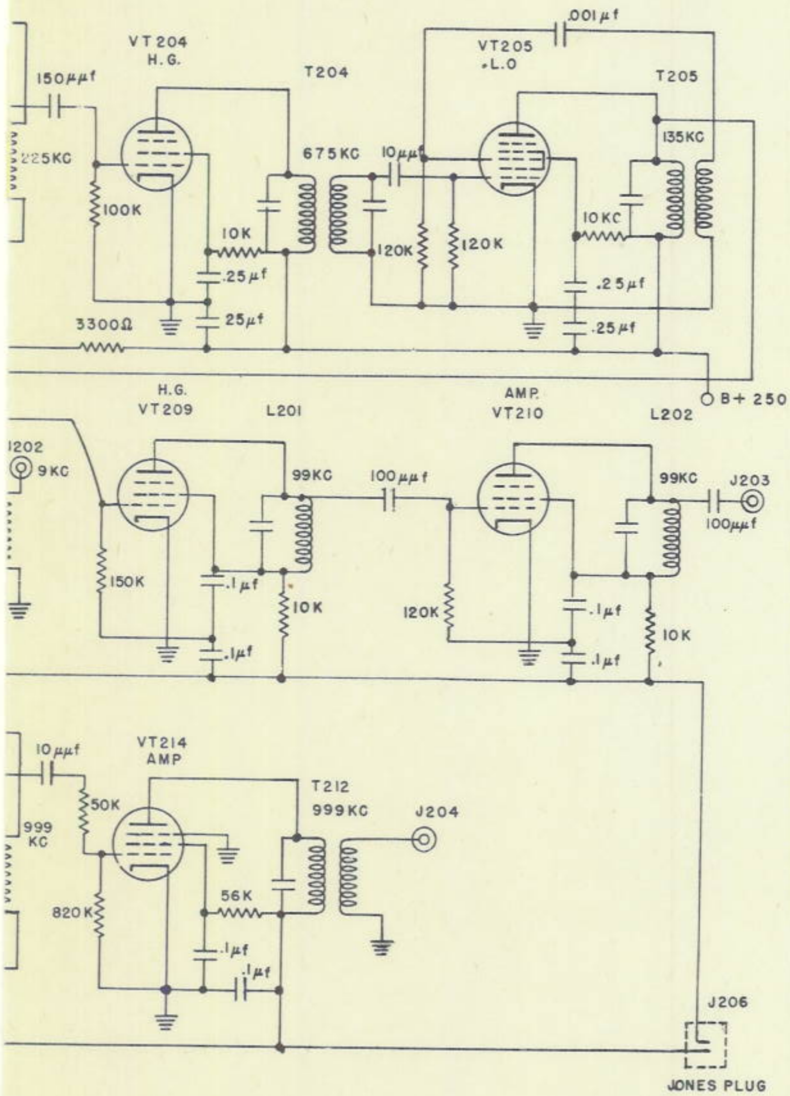


Figure 7 - Freq

X A

AGRAMS



VT201 - 6AC7
VT202 - 6AC7
VT203 - 6SA7
VT204 - 6AC7
VT205 - 6SA7
VT206 - 6SA7
VT207 - 6SA7
VT208 - 6AC7
VT209 - 6AC7
VT210 - 6AC7
VT211 - 6AC7
VT212 - 6AC7
VT213 - 6SA7
VT214 - 6AC7

L201 - Tuned 99 kc
L202 - Tuned 99 kc output
T201 - Double-tuned 300 kc
T202 - Double-tuned 900 kc
T203 - Tuned 225 kc; 1-1 turns ratio
T204 - Double-tuned 675 kc
T205 - Tuned 135 kc; 1-1 turns ratio
T206 - Tuned 45 kc; 1-1 turns ratio
T207 - Tuned 9 kc; 1-1 turns ratio
T208 - Tuned 9 kc output
T209 - Double-tuned 4995 kc
T210 - Tuned 4995 kc output
T211 - Tuned 999 kc; 1-1 turns ratio
T212 - Tuned 999 kc output

J201 - Input 100 kc
J202 - Output 9 kc
J203 - Output 99 kc
J204 - Output 999 kc
J205 - Output 4995 kc
J206 - 4-prong Jones plug

uency generator

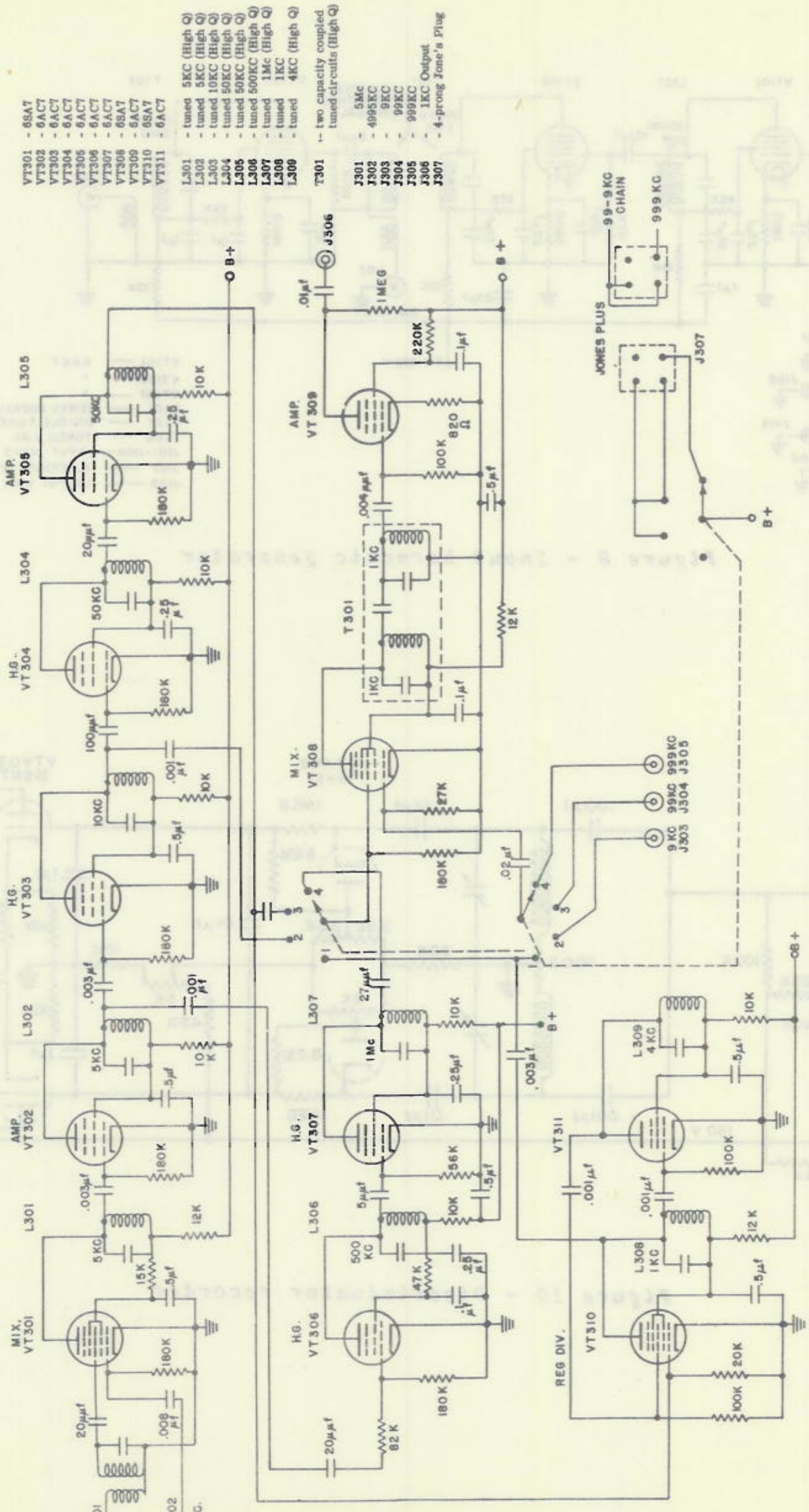


Figure 8 - Decade multiplier

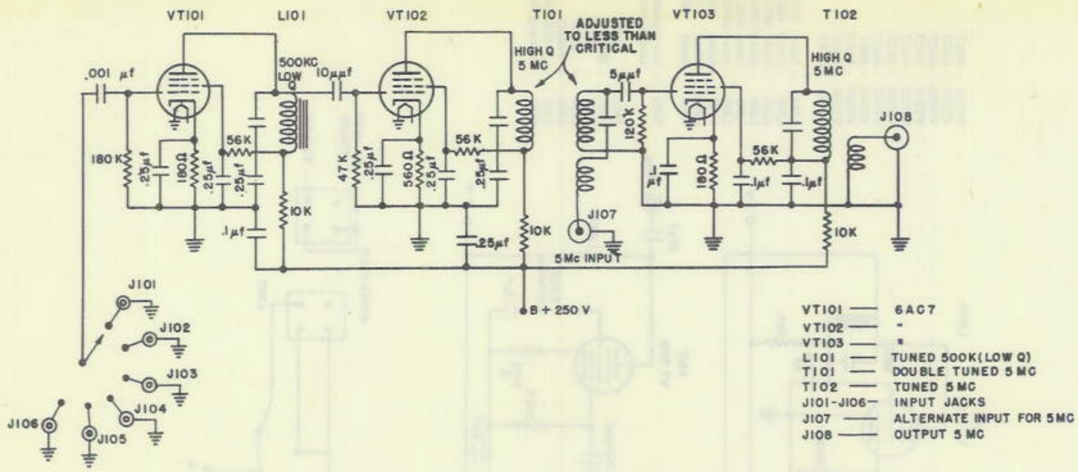


Figure 9 - Input harmonic generator

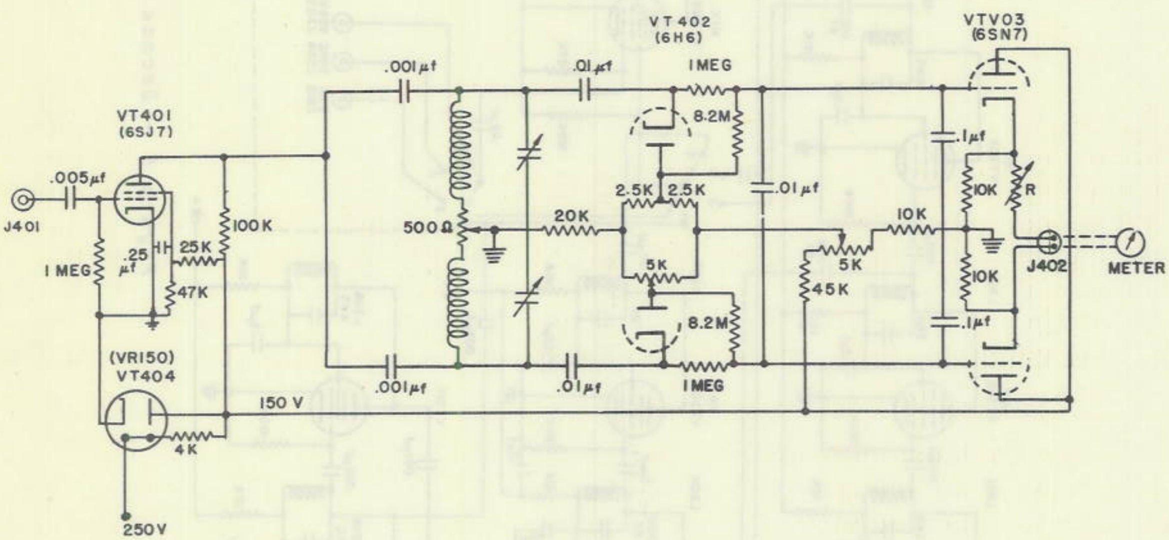


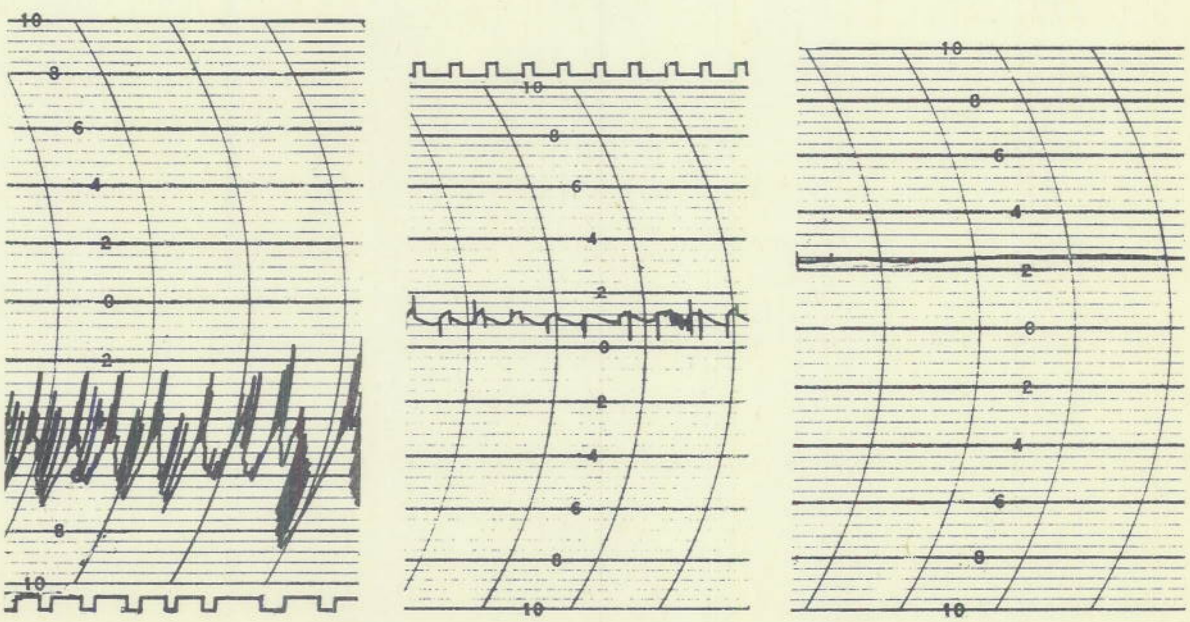
Figure 10 - Discriminator recorder

APPENDIX B

TYPICAL DATA

Oven Temperature Control vs. Output Frequency

The effect of the "oven temperature control" system upon output frequency is illustrated in Figure 11 for a standard-type oscillator. The parallel lines represent frequency deviations, each of the heavier lines being 2 parts at 10^9. The distance between the curved lines represents a 15-minute interval of time. The marking along the bottom (Figure 11a) and top (Figure 11b) of the paper indicates when heat is being supplied by the external heater. Figure 11a shows a swing of about 4 parts in 10^9, the interval of which roughly corresponds to that of the heater. Investigation of the system indicated that the heater was affecting a frequency-sensitive portion of the oscillator circuit. In Figure 11b this condition is remedied. However, a variation of about 1 part at 10^9 still appears and shows correlation with the heater. In Figure 11c the heater control is set so that heat is supplied continually and the effects are shown to be negligible in this condition.



11a   11b   11c

Figure 11 - Typical data

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